TWO-DIMENSIONAL FLOW MODELING FOR RIVERINE FORECASTING BY THE NATIONAL WEATHER SERVICE

by

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INTRODUCTION

Real-time riverine forecasting by the National Weather Service (NWS) is disseminated to the public via Weather Service Offices (WSO's) located in all states within the Nation. The WSO offices are assisted in the preparation of the riverine forecasts by regional offices called River Forecast Centers (RFC) and by the National Hurricane Center (NHC) in Miami. Riverine forecasts are primarily concerned with the prediction of water surface elevations at principal locations (river forecast points) along most of the major and many of the lesser rivers in times of flood, and at many locations on a daily frequency. The floods and lesser rises of the rivers may result from rainfall and/or snowmelt runoff, reservoir release flows, hurricane storm surges, and dam failures. In addition to water surface elevations, forecasts are often provided for flow discharges and velocities. Such forecasts are used for a multitude of purposes, e.g., water supply, navigation, irrigation, power, reservoir operation, recreation, and water quality interests.

Most forecasts are associated with the runoff emanating from precipitation or snowmelt. Conceptual hydrologic mathematical models are used to predict the quantity and temporal distribution of the runoff as it accumulates in well-defined channels (streams or rivers). The resulting flood wave propagates through the channel; and its magnitude, shape, and movement are predicted by other mathematical models known as flood routing models. These are based on the one-dimensional equations of unsteady flow. Most of these models are substantial simplifications of the complete equations. Propagation of waves due to storm surges or dam failures are predicted using the complete one-dimensional equations. Currently, NWS is slowly extending this type of flood routing prediction to those floods which propagate through large navigable rivers and estuaries of very mild hydraulic gradient (less than 2 ft/mi) which are subject to backwater effects due to large tributary inflows or tides.

The use of mathematical models based on two-dimensional flow equations is currently limited to the forecasting of coastal flooding due to hurricane-produced storm surges. The NHC utilizes a two-dimensional model, SPLASH, (Jelesnianski, 1972) for this purpose. In a few locations, the RFC's are prepared to use the forecasted storm surge to predict subsequent upstream flooding along coastal rivers.

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several flood-modeling improvements which will result from combining the features of DWOPER and DAMBRK, one such improvement will be in the treatment of dam-break floods spreading onto a wide flood plain as shown in Fig. 3. The FLDWAV model will be able to simulate the spreading of the flow onto the flood plain via a network of flow paths selected by the user according to the flood plain topography. Also, the use of the left flood plain, right flood plain, and channel routing option will provide additional descriptive capabilities for modeling the spreading flow. When used in this manner, the FLDWAV model, although one-dimensional, will provide a pseudo two-dimensional modeling capability while retaining the computational efficiency possible with an implicit one-dimensional model.

Consideration is being given to the need for using two-dimensional hydrodynamic equations for modeling dam-break floods spreading onto wide, flat flood plains where the topography does not aid the user in selecting particular flow paths. Some two-dimensional models for dam-break flows have been reported in the literature; e.g., Xanthopoulous and Koutitas, 1976; Richert, 1977; and Katapodes and Strelkoff, 1979. Some considerations in the use of the two-dimensional unsteady flow equations involve the following considerations: (1) A significant increase in computational requirements. (2) An inability for real-time forecasting due to data input complexities and computational requirements. (3) The additional expected accuracy may not be consistent with the present dam-break modeling capabilities in which considerable error in the predicted dam-break outflow hydrograph exists due to the state of the art in predicting the formation of the breach in a concrete, earthen, or rock-fill dam. (4) The inherent lack of precision in two-dimensional modeling of flows spreading onto dry areas. (5) The development effort to make the two-dimensional model as versatile as the existing DAMBRK model. (6) The relatively few instances where a two-dimensional approach is clearly needed.

FORECASTING IN ESTUARINE NETWORKS

At the present, NWS provides very limited real-time flow forecasting in complex estuarine networks such as shown in Fig. 4. This is accomplished using the one-dimensional DWOPER model and is generally satisfactory for predicting water surface elevations and the average velocities along the major flow axes. However, for possible future real-time forecasting of chemical or oil spill emergencies occurring in such complex waterways, improvement of such forecasts could be possible by using the two-dimensional hydrodynamic equations. A review of many two-dimensional hydrodynamic models was reported by Hinwood and Wallis, 1975. For real-time applications where computational efficiency is desirable, the implicit type finite difference solutions of the two-dimensional equations, e.g., Grubert, 1976, and Niemeyer, 1979, would be preferable.

SUMMARY

The use of two-dimensional flow models for riverine forecasting by NWS is very limited at the present time. The two-dimensional hurricane surge

This paper briefly describes the current procedure for river forecasting of hurricane storm surge flooding. Also, considerations for possible future use of other two-dimensional flow models are discussed with respect to: a) two-dimensional porous media flow in aquifers which significantly interact with adjacent rivers, b) two-dimensional surface flow associated with dam-break floods propagating in wide, flat flood plains, and c) two-dimensional surface flow in complex channel networks associated with estuaries.

RIVERINE FORECASTING OF HURRICANE STORM SURGES

Real-time forecasting of river flooding due to hurricane-produced storm surges is presently in operation for the lower portions of the Mississippi, Sabine, and Neches Rivers as shown in Figures 1 and 2. Work is on-going to gradually extend this service to other Gulf Coast rivers in Texas. As indicated in the figures, two numerical hydrodynamic models are used to forecast this type of flooding. The hurricane-generated storm surge is predicted using the SPLASH model (Jelesnianski, 1967, 1972, 1976) and the subsequent upstream propagation of the surge within the confines of a coastal river is predicted using the DWOPER model (Fread, 1978, 1981).

SPLASH is a two-dimensional, vertically integrated hydrodynamic model. Externally specified meteorological parameters are utilized to generate the hurricane wind field. These parameters are (a) the radial distance and pressure drop from the storm center to its periphery, and (b) the forward speed of the storm. The wind field submodel empirically computes the maximum wind speed in a stationary storm and generates the wind field by dynamically balancing the computed wind speed, pressure gradient, and inflow angle fields. The computed wind field is then incorporated into the two-dimensional hydrodynamic equation through the wind stress term which drives the model, i.e., causes the development of the storm surge.

The governing partial differential hydrodynamic equations of SPLASH are numerically solved using an explicit finite difference technique. Terms relating to the water depth are linearized such that the computed surge height is not added to the undisturbed depth during the computations. Bottom friction is treated using the Ekman principle. The computational grid size is approximately 4 miles and computed results are presented 8 miles apart along the coast. The computational grid network is centered at a specified coastal location. The network width (along the coast) is 600 miles, and it extends seaward either 72 miles or the width of the continental shelf (whichever is larger). The boundary conditions consist of a vertical wall condition along the coast, a barometric pressure effect along the seaward boundary, and zero transport normal to the lateral open boundaries. The most recently published version of SPLASH (Jelesnianski, 1976) uses a sheared and stretched coordinate system along a mildly curved coastline with grid distances that vary from shore to deep water. At this time work is nearly completed in the development of the SLOSH model, which is an expanded version of SPLASH having the capability to treat overtopping of finite barrier heights to allow coastal flooding.

The coupling of the two-dimensional porous media flow model with the one-dimensional DWOPER streamflow model will be internal according to the following scheme (Freeze, 1971): (1) At each time step solve the porous media model using the stream water surface elevation from the previous time step as the specified head condition at the boundary of the subsurface flow system. (2) Use subsurface flow computed at the boundary by the porous media model as lateral inflow/outflow for the stream at that time step and solve the DWOPER model for new water surface elevations. (3) Use the new water surface elevations as the specified head condition for computing the subsurface flow using the porous media model. (4) Continue this alternating cycle until successive water surface elevations differ by less than an acceptable tolerance, then proceed to the next time step. Computational efficiency will be enhanced by extrapolating the stream water surface elevations computed at previous time steps for use in step (1), and by using different size time steps for the two models based upon the individual flow response of each flow system; coupling of the two models will occur only when the smaller time step advances that model's computations to the same point in time that the larger time step has caused the other model to reach.

Data requirements for the DWOPER model consist of cross-sectional top widths and Manning's n roughness coefficients; the porous media model requires the hydraulic conductivity and the moisture content parameters. Since the porous media model parameters are generally not directly available, it is anticipated that practical implementation of the coupled model will be based on the determination of these parameters via model calibration using observed streamflow hydrographs.

DAM-BREAK FLOOD FORECASTING IN WIDE FLOOD PLAINS

Real-time forecasting and pre-computation of possible or imminent dam-break floods is accomplished by the NWS DAMBRK model (Fread, 1980, 1981). This model predicts the time-dependent outflow from a reservoir due to spillway flows, overtopping flows, and discharge through a time-dependent, variable-geometry dam breach whose characteristics are supplied by the model user. The outflow is then routed through the downstream channel-valley using the complete one-dimensional equations of unsteady flow, which are solved by the same weighted nonlinear implicit finite difference technique used in the DWOPER model. The model is capable of including downstream dams or bridge-road embankments and lateral inflows. The flows may be either completely subcritical or supercritical for all times and locations during the simulation. The treatment of channel-valley cross-sections may be either as composite sections with dead storage areas or as separate channel, left flood plain, and right flood plain sections. The latter technique, although still a one-dimensional approach, allows for better treatment of the variance between flood plain flow and the meandering river channel flow. Computational efficiency, wide applicability, and user convenience are design features of the DAMBRK model which make it suitable for real-time flood forecasting.

Work is proceeding within HRL to combine all of the capabilites of the DAMBRK and DWOPER models into a new one-dimensional model (FLDWAV). Of the

DWOPER is a one-dimensional hydrodynamic model. It is a general purpose river routing model. One of its capabilities is to propagate a storm surge (introduced at the downstream boundary as a time history of water surface elevations) upstream along the river. The governing partial differential hydrodynamic equations are numerically solved using a weighted nonlinear implicit finite difference technique. Newton-Raphson iteration, combined with an optimally efficient quad-diagonal matrix solution algorithm, allow DWOPER to be very computationally efficient. The model can be used on branched river channels, either dendritic (tree-type) or bifurcated networks. It treats levee overtopping and failure, lateral inflows, irregular channel geometry, space and depth-dependent boundary friction (Manning type), and variable grid spacing. Nonlinear numerical stability is enhanced with an internal time step reduction algorithm.

The SPLASH model predicts the time history of the water surface elevation due to the storm surge at the mouth of the river. DWOPER uses this as its downstream boundary condition and a specified discharge hydrograph as its upstream boundary. The upstream boundary is located considerably beyond the last point of interest where it is assumed the surge has insignificant effect on the specified discharge. The coupling between SPLASH and DWOPER is external in the sense that the surge propagation into the river is not treated during the SPLASH computations. Athough it is recognized that such external coupling of the two models is not ideal, it is nevertheless considered the practical choice due to such factors as (a) dampening of the coupling effect as the surge propagates further upstream; (b) the models were developed and are maintained and operationally used by three separate divisions of NWS; and (c) the real-time use of the models.

COUPLED STREAMFLOW-POROUS MEDIA FLOW MODEL

Work is proceeding at the NWS Hydrologic Research Laboratory (HRL) to develop a two-dimensional porous media flow model which will be internally coupled to the DWOPER model. The combined model will be used to improve streamflow forecasts where flow exchanges occur between the river and the adjacent groundwater aquifer. Where the river is bounded by highly permeable alluvium, the flow interactions can be of sufficient magnitude to significantly affect the river flow by attenuating the peak flow, reducing the wave peak celerity, and extending the recession limb of the river discharge hydrograph. The river flow exchanges with the surrounding aquifer via saturated flow through the bed and banks of the river (Pinder and Sauer, 1971) and via unsaturated-saturated infiltration through the inundated river flood plain (Freeze, 1971).

The flow within the aquifer is modeled by combining the one-dimensional saturated porous media flow equations (flow is assumed to occur only in the direction perpendicular to the river axis) with the one-dimensional unsaturated porous media flow equations for flow occurring in the vertical direction. The resulting two-dimensional nonhomogenous, anisotropic porous media flow equations will be numerically solved using a weighted, nonlinear implicit finite difference technique with variable grid spacing. The model will utilize Newton-Raphson iteration and a specialized, highly efficient matrix solution algorithm.

model (SPLASH) is used to generate the surge at the mouth of some Gulf Coast rivers where the riverine forecasting of the surge propagation upstream is then accomplished with a one-dimensional routing model (DWOPER). Development is under way to use a two-dimensional porous media flow model internally coupled to DWOPER for real-time forecasting of rivers significantly affected by flow exchanges with the adjacent groundwater aquifer. Possible future use of the two-dimensional hydrodynamic equations includes (a) spreading of dam-break floods onto wide, flat flood plains, and (b) chemical-oil spill forecasting in complex estuarine networks.

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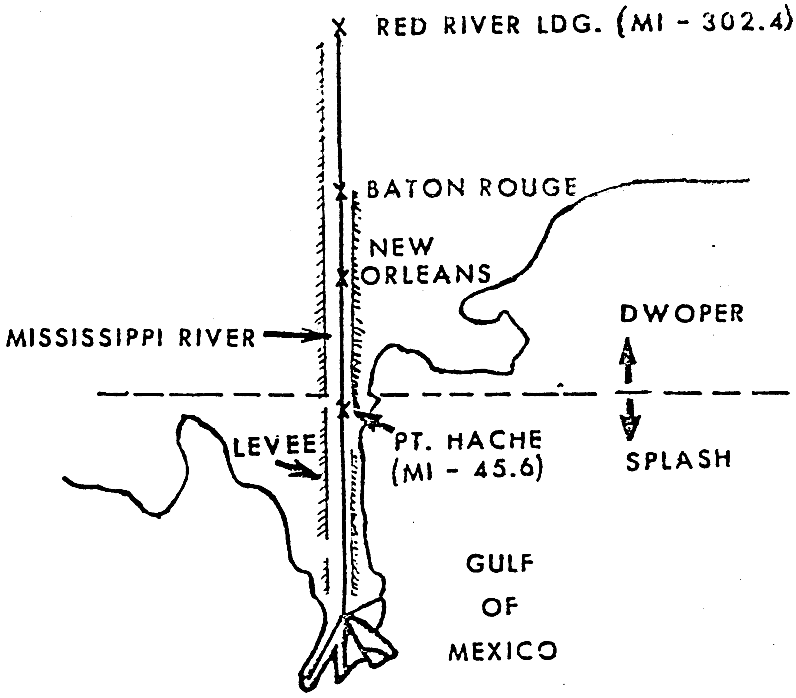

FIG. 1– HURRICANE STORM SURGE FORECASTING OF LOWER MISSISSIPPI RIVER

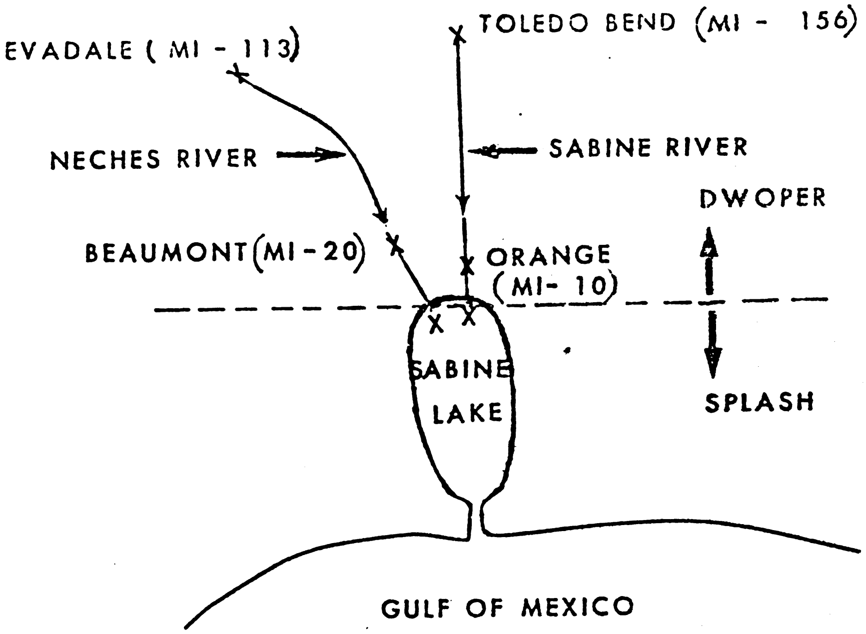

FIG. 2–HURRICANE STORM SURGE FORECASTING OF SABINE AND NECHES RIVERS

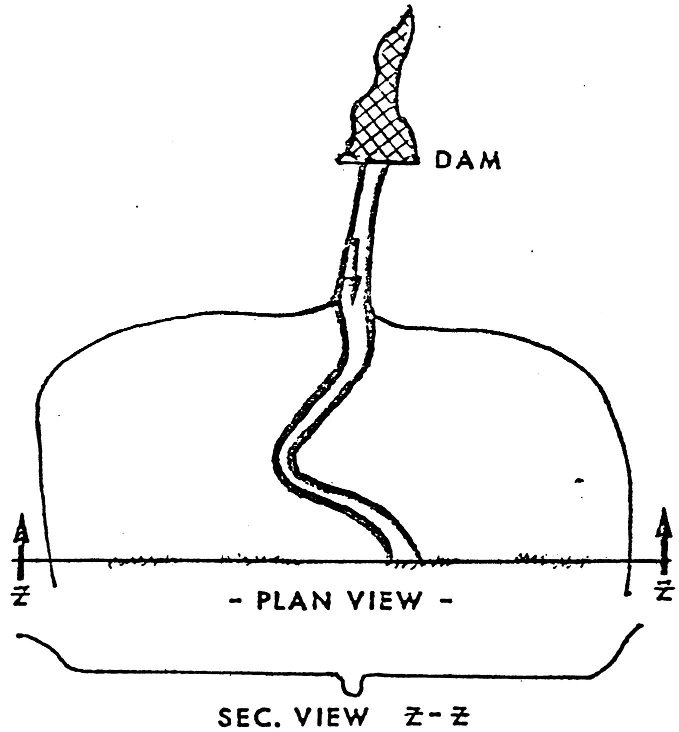

FIG. 3– DAM–BREAK FLOOD ONTO A VERY WIDE, FLAT FLOOD PLAIN

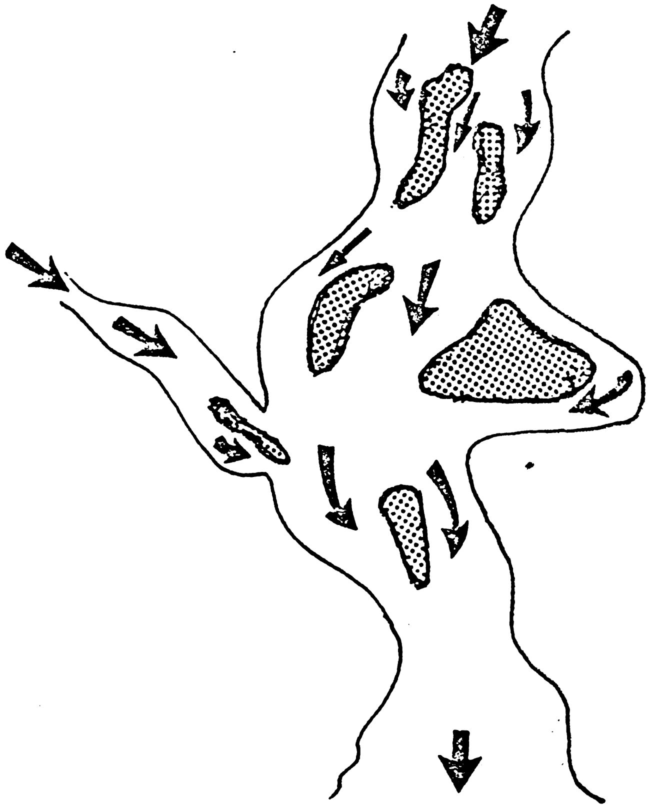

FIG. 4 –COMPLEX FLOWS IN RIVERINE – ESTUARINE NETWORKS

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Question: When will the new one-dimensional combined model (FLDWAV) be available?

Dr. Fread: The FLDWAV model is not yet operational; however, all the components have been developed and tested in other models (DWOPER and DAMBRK). They have been re-written in a completely new code which has taken the last several months to develop; currently, we are in the process of debugging the new code and hope to have it available by next spring.

Question: Could you explain more about the numbering system you use for modeling flow networks with the FLDWAV model? You talked about maintaining computational efficiency with the implicit formulation, and I would like to know more about it.

Dr. Fread: The network solution scheme used in FLDWAV is not a completely general network solution; however, I think it will treat almost all practical riverine networks. It will treat any order of dendritic (tree-type) network and/or bifurcations around islands with either zero, one, or two bypasses; the dendritic system can join any portion of the bifurcated branches; and a dendritic network associated with river delta formations can also be treated. Each type of flow junction is given a special code number by the user. This code allows the three conservation equations at each junction to be assembled in the general coefficient matrix of simultaneous equations for the entire river system in such a way as to minimize the creation of off-diagonal elements and to minimize the creation of new off-diagonal elements during the elimination phase of the matrix solution algorithm. Also, the way in which the cross-sections are assigned sequential numbers within the river system is most important in effecting the desired minimization. The numbering scheme is as follows: numbers run consecutively in the downstream direction until a dendritic-type junction is reached; then the most upstream section of the dendritic branch is given the next consecutive number and the numbers increase in the downstream direction along this branch until another junction is reached; then the most upstream section of that dendritic branch is numbered next and the numbers increase in the downstream direction along that branch until a new junction is reached; this is repeated until all sections have been numbered down to the very first dendritic-type junction; then the numbers continue to increase along the downstream branch of this junction; bifurcations are numbered in a similar manner. The computational efficiency is achieved by use of a specially developed matrix solution technique of the Gauss elimination type which only operates on non-zero elements in the matrix through use of the user-specified code number which was assigned to each junction in the river system.

Question: How do you treat delta's as dendritic branches?

Dr. Fread: The numbering scheme is the same, but the model treats the flows which are directed in the downstream direction as negative flows.

Question: We have had situations using the DAMBRK model where the flow was supercritical in the channel and subcritical in the overbank. How can you use the model in this situation?

Dr. Fread: Within the present limitations of the DAMBRK model, perhaps you could increase the roughness associated with the in-bank flows to force this flow into the subcritical regime. This could be done if the in-bank flows were only a small portion of the total flow which is generally the case in modeling dam-break floods.

Question: What about supercritical flow in the FLDWAV model?

Dr. Fread: The FLDWAV model can simulate either subcritical or supercritical flow but not a mixture of the two types of flow in space or in time. One of our research efforts is to develop an algorithm to enable an implicit model to simulate mixed subcritical-supercritical flows.

Question: In your research concerning subcritical-supercritical flows, do you think the following scheme would work? At any given time determine where subcritical and supercritical flows are, then for the next time step use as a downstream boundary condition for any subcritical reach a critical flow rating curve and solve that part of the system separately. Then the four-point implicit scheme becomes a two-point scheme, and starting at the upstream end of the supercritical reach, solve section-by-section in the downstream direction; the final solution in the supercritical reach provides an upstream boundary condition for the next subcritical reach, and so on.

Dr. Fread: I think that scheme is a feasible approach although it is not the only one I am investigating. I am also trying to treat the entire system simultaneously by using internal boundaries where flows change from one regime to the other. At the internal boundaries, the appropriate transition equations such as critical flow or sequent depth are substituted for the momentum equation.

Question: How do you handle obstructions such as bridges in the FLDWAV network system?

Dr. Fread: Bridges are treated in the FLDWAV model the same way they are in the DAMBRK model, i.e., as internal boundaries which may be located anywhere in the flow system. The flow through the bridge is modeled as orifice-type flow and flow which overtops the bridge embankment is treated as broad-crested weir flow. Other internal boundaries could be used for sections having (1) a specified rating curve, (2) critical flow as at a waterfall, or (3) a dam where the flow could be any combination of spillway, overtopping, and/or breach flows. At internal boundaries the continuity and momentum equations are replaced with the appropriate flow equation and a simple continuity equation ($Q_i = Q_{i+1}$). The internal boundary equations are then solved simultaneously along with the upstream and downstream boundaries and the one-dimensional continuity and momentum equations of unsteady flow.

Question: How does the DWOPER model handle levee overtopping such as in the lower Mississippi River application?

Dr. Fread: Levee overtopping is an inherent capability of the DWOPER model; however, this has not been implemented by our field office for storm surge forecasting of the lower Mississippi River. They have chosen not to use this capability since they are primarily concerned with predicting stages below the levee crests and simply determining if the levees will be overtopped. The levee overtopping feature has been used in other applications, e.g., the lower St. Johns River in New Brunswick, Canada, and the Susquehanna River. The Corps district office in Baltimore took only a few days to calibrate by trial-error the DWOPER model for the Hurricane Agnes flood of 1972. Calibration consisted of adjusting the Manning n and the weir discharge coefficients.

Question: What about submergence effects in levee overtopping?

Dr. Fread: In both the DWOPER and FLDWAV models, the standard relationships for broad-crested weir submergence are used. This is possible since flows and depths are simulated on both sides of the levee.

Question: Do you iterate during the levee overtopping computations?

Dr. Fread: Yes, iteration is used since the flow in each river (main river and a river representing the flood plain flow) are solved through an iteration process. The main river is first solved; then the flood-plain river is solved. If the flow conditions at the junction of the two rivers are compatible within a specified tolerance, the solutions are accepted and the computations are advanced in time. Thus, the feedback between the water levels on each side of the levee is accomplished via the iteration process. Also, reverse flows across the levee can be treated, e.g., if the river level falls much faster than the level in the flood plain, reverse flow could occur if the flood-plain level remained above the levee crest. If flow reverses its original direction due to a reversal of the relative water surface elevations in the river and in the flood plain, the computed broad-crested weir flow corrected for submergence is assigned a negative sign. Flows in this range are limited in their accuracy since the submergence relationship is least reliable when the differential head is small. Also, relatively large flow changes can occur for small changes in water levels for flows in this range. This can necessitate the use of smaller computational time steps to maintain numerical stability. This is accomplished automatically within the models.

Question: Can you model erosion (overtopping) failures of the levee?

Dr. Fread: Yes, the DWOPER and FLDWAV models have this capability; however, the user must specify the length of the levee failure (crevasse) and the elapsed time for its complete formation.

Question: What is the nature of the automatic time step adjustments in the DAMBRK, DWOPER, and FLDWAV models?

Dr. Fread: These models have an automatic procedure contained within the finite difference solution algorithm to increase the robust nature of the four-point implicit method. Rapidly rising hydrographs and non-linear properties of the cross-sections due to variations in the vertical and/or along the x-axis may cause computational problems which are manifested by non-convergence in the Newton-Raphson iteration or by erroneously low computed depths at the leading edge of steep-fronted waves. When either of these manifestations are sensed, an automatic procedure consisting of two parts is implemented. The first reduces the current time step (Δt) by a factor of 1/2 and repeats the computations. If the same problem persists, Δt is again halved and the computations repeated. This continues until a successful solution is obtained or the time step has been reduced to 1/16 of the original size. If a successful solution is obtained, the computational process proceeds to the next time level using the original Δt. If the solution using $\Delta t/16$ is unsuccessful, the Θ weighting factor is increased by 0.1 and a time step of $\Delta t/2$ is used. Upon achieving a successful solution, Θ and the time step are restored to their original values. Unsuccessful solutions are treated by increasing Θ and repeating the computation until $\Theta = 1.0$, whereupon the automatic procedure terminates, and the solution with $\Theta = 1.$ and $\Delta t/2$ is used to advance the solution forward in time now using the original Θ and Δt values. Often, computational problems can be overcome via one or two reductions in the time step.

Question: In a developed, urbanized area where there is a lot of housing, how do you handle the friction in the flood plains?

Dr. Fread: The models allow the Manning n to be a specified function of water surface elevation. Thus the n value assigned to the water elevations within the flood plain, where the houses affect the flow resistance, could account for the frictional effects occurring at that time. Trial-error adjustments of the n values during successive model runs could be used to determine the appropriate n values if observed stages and discharges are available. When observed flood-plain flows are not available, which is generally the case when modeling most dam-break floods and storm-surge floods, the Darcy formula can be used as an objective method to determine the proper Manning n to be used in the model. As in the Colebrook-White friction formula, the Darcy f is thought to be composed of two types of friction: (1) submerged friction expressed via a Nikuradse type roughness relation, and (2) partially submerged friction using density and spacing of the partially submerged obstructions along with their appropriate drag coefficients. Then the Manning n can be hand-computed from the Darcy f.

Question: What about the status of the streamflow-aquifer model?

Dr. Fread: Primary development of the aquifer component is just getting started. I would estimate that it will be two years before it will be available.

Question: Will you have enough data to calibrate the streamflow-aquifer model?

Dr. Fread: When testing the streamflow-aquifer model our intent is to use data sets that have cross-sections, observed streamflow stage and discharge hydrographs, and, if possible, some groundwater levels. For general field implementation of the model, it is anticipated that the groundwater levels will not be available. Since our intent in developing the stream-aquifer model is to improve the streamflow prediction, we think we can simply calibrate the parameters in the aquifer model to best reproduce observed streamflow stages and discharges.